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TURBINE FLOWMETERS AND THEIR APPLICATIONS AT THE NAVAL AIR PROPULSION CENTER

By R. E. OBERNDORFER

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At the Naval Air Propulsion Center, ~~we~~ have a specific requirement to make accurate mass flow measurements on the fuel flow of a gas turbine engine to determine the performance characteristics. The problem of acquiring mass flow from the inherent volumetric flow data of a turbine flowmeter is discussed. The development of a universal curve from calibration data is discussed. The unique curve fits for flowmeter, viscosity and specific
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20. gravity and their use during on-line data acquisition is described. The accuracy of the final mass flow data and its dependence on the errors associated with viscosity, specific gravity, temperature and frequency measurement is discussed. Some techniques used at NAPC to reduce these errors are described.

NAVAL AIR PROPULSION CENTER

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MEASUREMENT AND INFORMATION SYSTEMS DEPARTMENT

NAPC-MS-34 APRIL 1980

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INTRODUCTION

At the Naval Air Propulsion Center (NAPC), the accurate measurement of mass flow rates of fuel to a gas turbine engine is required to determine the performance characteristics of the engine. Over the past several years NAPC has been looking at various techniques to improve the method of fuel flow measurement. The objective was to provide a technique for calibrating flowmeters for use in tests with extreme fuel temperatures. At project initiation, the NAPC calibration facility consisted of several weigh-time systems that required expensive fluid temperature conditioning for cold calibrations. The weigh-time systems could not be run at high temperatures due to their open system design. New fuels with high viscosities, high densities, and corrosive characteristics increased the need for a renovation of the NAPC flow measurement and calibration procedure.

To document the improved procedure used at NAPC, some of the problem areas that were encountered, and to provide a reference for other users of turbine flowmeters, it was decided to publish this report. It is the intent of this report to provide methods required to make accurate measurements with turbine flowmeters. The report has been divided into specific sections. A section on flowmeter mechanics is included for those who are new to turbine flowmeters. The section on response characteristics is included for those interested in the details and problems of flow measurement. A section on calibration techniques is included to provide reference to sections on data acquisition, and processing. The section on data acquisition covers acquisition from frequency counters as well as automatic acquisition and processing equipment as used at NAPC. A discussion of trade-offs of simplicity of measurement and the accuracy of the measurement is included. Appendix A discusses the NAPC calibration facility, Appendix B discusses the NAPC processing techniques, and Appendix C includes accuracy estimates for various techniques of flow measurement using turbine flowmeters.

Throughout the paper the application of the turbine flowmeter is restricted to the use experienced at NAPC. At NAPC, the flow rate of hydrocarbon fluids (specifically JP-4, JP-5, JP-9, and RJ-4 fuels) is measured. Water flow is also measured, but with less required precision. Stoddard solvent (Mil 7024C), and blends with hydraulic fluid (Mil 5606), or synthetic oil (Mil 23699) are used in the calibration facility to provide a range of viscosity at ambient temperatures to simulate the viscosities at the extremes of temperatures used for test cell running. Viscosities from .8 to 40 centistokes are the extremes encountered when running JP-4 fuel at 120°F (49°C) or JP-9 fuel at -40°F (-40°C), respectively.

Flowmeter sizes in use at NAPC range from 3/8 inch (AN 06) to two inches (AN 32) with flow ranges from .05 to 225 gallons per minute (20 to 85500 pounds per hour). In some engine applications, more than one size flowmeter is used to cover the full flow range.

Most of the material included is available in the references. Flowmeter manufacturers should be consulted for special applications or meter design.

DISCUSSION

A. FLOWMETER MECHANICS

The flowmeter that is referenced throughout this document is the turbine flowmeter. There are several manufacturers of turbine flowmeters with basically the same designs. They consist of a body, rotor, support bearings for the rotor, inlet straightening vanes, and an electrical pickoff. Figure 1 is a disassembly of a typical, extended range meter.

Each manufacturer uses different designs of the rotor blade shape, to provide a maximum linear region of flow. Complexity of shape, manufacturing costs, and response characteristics are traded to obtain the best results.

Bearing materials and design are tailored for various applications from water to acidic or corrosive fluids. Brass or graphite journal bearings, or stainless steel or carbon ball bearings may be used, depending on the application. To measure hydrocarbon fluid flow, stainless steel ball bearing flowmeters are used.

Pickoffs are of two designs, the magnetic type and the reluctance coil type referred to as an rf pickoff. Initially permanent magnet pickoffs were used to detect rotor passage and generate an electrical signal proportional to flow rate. The magnetic pickoff generates a drag on the rotor that decreases the low flow capability of a flowmeter. A reluctance pickoff was designed using a coil driven by a high frequency. Rotor passage modulates the frequency to provide a signal proportional to flow rate. The reluctance type of pickoff generates no drag on the rotor element and can be used at lower flow rates.

B. RESPONSE CHARACTERISTICS

Rotor shape, bearing and pickoff type influence the response characteristics of a turbine flowmeter. For a given fluid, increased drag, due to bearing friction and magnetic force from the pickoff-rotor interaction, decreases the linear range of a flowmeter. To reduce the drag, stainless steel ball bearings and reluctance type pickoffs are used to provide the best range for the hydrocarbon fuels used in gas turbine engines. Figure 2 illustrates the effects of ickoff and bearing type on rotor drag. As the fluid flow decreases, there is less force available to turn the rotor and the retarding forces have a greater effect.

Rotor shape can be changed to affect the shape of the curve. A rotor can be made that is more efficient in the transition region between laminar and turbulent flow resulting in a curve shape as seen in Figure 3. In general, any flow, retarding mechanism results in a decrease in cycles per gallon output at low flows, where the fluid forces are low. The larger the retarding force (more magnetic drag or higher viscosity) the greater the decrease in cycles per gallon output. Viscosity is grouped into this category since increased viscosity causes a greater retarding force.

Figure 4 indicates the change in flowmeter response due to changes in viscosity for a single meter. The top curve in the plot is for fluid flow with a viscosity of 1.21 centistokes. It is approximately linear with flow rate. The other curves, with viscosities of 10.2 and 14.1 centistokes, become non-linear at lower flow rates.

The various changes in response characteristics are tailored to provide the most linear flowmeter response. The mechanical aspects, bearings, pickoff, and rotor design, then become constant for a particular meter. The output signal from a meter, a series of pulses, is a function of fluid flow rate. After investigating meter response and fluid characteristics, the response is seen to be a function of Reynold's number. Good correlation over a wide range shows that:

$$fo = f(Re)$$

where: fo = output frequency (Hertz)
Re = Reynold's No.

Reynold's number is a dimensionless parameter defined to be:

$$Re = \frac{VD\rho}{\mu}$$

where: ρ = fluid density
V = fluid velocity
D = pipe diameter
μ = absolute viscosity

kinematic viscosity ν is defined as:

$$\nu = \mu/\rho$$

then $Re = \dfrac{VD}{\nu}$

For a given flowmeter the diameter and other mechanical characteristics are constant. So that:

$$fo = f(V/\nu)$$

The output frequency is affected by increasing viscosity because of an increased retarding torque on the rotor. At low flow rates there is insufficient fluid energy to overcome the viscous forces and the response of the meter becomes non-linear. Increased viscosity also changes the inlet velocity profile to the meter.

To characterize a flowmeter over a wide range of operation, it is necessary to use viscosity as a normalizing factor. This technique, called the universal curve, is based on pulses per gallon correlated with frequency (Hertz) divided by viscosity (centistokes). Frequency can be measured and is the signal produced by the pickoff on the flowmeter. From the calibration of the flowmeter and a known viscosity, flow rate can be determined.

Figure 5 presents the universal curve of the data shown in Figure 4 corrected for viscosity. By using this technique a flowmeter can be characterized by a single curve over a wide range of operation.

From the discussion of response characteristics it must be stressed that the turbine flowmeter is a volumetric device. In application it is used to measure mass flow in pounds per hour. The conversion from volume to mass flow is done using the specific gravity of the fluid being measured at the temperature encountered during the engine test. Initially calibrations were provided on the fuels to be used at the temperatures that were expected to be encountered. Figure 6 shows the results of three calibrations displayed in mass flow units for typical fuels and temperatures. The data points in Figure 6 are mass flow calculated from the data presented in Figures 4 and 5. The technique of mass flow calibration is adequate if it can be guaranteed that the meter will be used on a fluid having the same specific gravity as the calibration. If it does not, the curve is shifted proportionally to the change in specific gravity.

C. INSTALLATION REQUIREMENTS

The response characteristics can be improved by proper installation of the flowmeter. For best accuracy the flow should be uniform at the entrance to the flowmeter. To establish a uniform flow, it is recommended that at least ten diameters of straight pipe be installed upstream of the flowmeter. To prevent interaction from downstream effects, five diameters of straight pipe are recommended downstream. It is not always possible to calibrate the flowmeters in the configuration to be used during the engine test. By meeting these minimum straight pipe requirements in both test and calibration, satisfactory results can be obtained without using the test-installed configuration.

Another requirement for installation is the measurement of the temperature of the fluid, especially if mass flow is required. If large temperature differences exist between the temperature measurement station and the flowmeter, some technique should be used to acquire temperature at the meter. A suitable technique is to measure temperature both upstream and downstream and use an average to obtain temperature at the flowmeter. It should be noted that a thermocouple probe into the flow stream should be a minimum of ten diameters upstream or five diameters downstream. To insure temperature uniformity, insulation may be used to prevent temperature changes over the measuring section.

D. CALIBRATION

A flowmeter is a volumetric device and the objective of calibration is to determine the response characteristics when provided with a known flow rate. The response can be shown to be:

$$fo = f(V/\nu)$$

where: f_o = output frequency
V = flow rate
ν = viscosity

During calibration a fluid is used with constant viscosity over the calibration run so that:

$$f_o = f(V)$$

and, in calibration, the flow rate is known so that the response characteristics can be established. In application the flow rate is the required parameter so

$$V = f(f_o) \text{ or}$$

$$V = f(f_o/\nu)$$

is used for a wide range of flow and viscosities.

A discussion and derivation of this relationship is provided in the section on Response Characteristics and in references (1) through (6).

During calibration, the flow is varied such that the flowmeter produces 200 to 2000 Hz, and data relating frequency output to flow rate is obtained. The range of 200 to 2000 Hz is typically the linear range of an rf type flowmeter and is the area of highest accuracy. To provide data for a wide range of applications, several fluids of different viscosities are used for calibrations. The data can then be combined into a single function that defines the range of flowmeter operation.

To provide a calibration for a flowmeter, a constant flow rate is required. Several techniques are currently used to satisfy the requirements. Basically, a known volume or mass is passed through the meter. Pulses from the meter and the time required to flow the known volume or mass through the meter are measured. References (7) through (10) discuss in detail various calibration techniques. The principal alternatives currently in use are weigh-time techniques and ballistic techniques.

The weigh-time technique consists of establishing a flow rate through the flowmeter and then measuring the time it takes to flow a specific weight of fluid. The result is a correlation of frequency output to pounds per hour flow rate. Temperature and specific gravity are the critical parameters in the conversions back to volumetric flow. If the data is not converted to volumetric, results similar to Figure 6 will be obtained if several fluids are used.

The ballistic technique consists of measuring the time required to flow a known volume. Flow rate is established just prior to the measurement. Temperature is required in this technique for viscosity correlation. The data is reported in volumetric form. The technique used at NAPC is the ballistic technique and it is discussed in Appendix A.

A third technique may be used with a resultant greater uncertainty. Two flowmeters, one with known characteristics may be piped together, in series with a pump. A comparison between the known flowmeter and unknown meter will characterize the unknown flowmeter.

E. DATA ACQUISITION

In applications at NAPC, data is acquired through a computer controlled data acquisiton system. The computer processes the data on-line and provides the capability of using curve fit data to generate engineering units from the frequency of the turbine flowmeter. Several parameters are required to determine the fuel flow in pounds per hour units. The calibration data is given as a function of volume flow and viscosity, and the parameters required for conversion to mass flow are specific gravity and viscosity.

For best accuracy, it is required to know specific gravity and viscosity for the specific fuel used, since they vary from batch to batch. At NAPC, prior to test, a fuel sample from the batch of fuel to be used during engine testing is analyzed for its characteristic properties of specific gravity and viscosity. Viscosity is measured at three temperatures and a set of coefficients is generated to curve fit viscosity against temperature. Specific gravity is measured at 60°F (15.6°C). This establishes one of a family of curves of specific gravity versus temperature. This family of curves all have equal slope.

During testing, a measurement of fluid temperature at the flowmeter is used to determine viscosity and specific gravity. Flowmeter frequency output is also measured. The conversion process uses frequency and viscosity to extract volumetric flow rate from the calibration curve and specific gravity is used to convert to mass flow rate.

Temperature is a critical parameter in the determination of mass flow rate. The conversion from volumetric flow to mass flow is a function of specific gravity and specific gravity is a function of temperature. For hydrocarbon liquids, the function is such that an uncertainty of 1°F in temperature produces a .05% uncertainty in specific gravity. Temperature measurements are made using thermocouples. The uncertainty for E-type thermocouples (Chromel-Constantan) is ± 3°F which corresponds to a $\pm .15$% uncertainty in specific gravity. The specific gravity uncertainty directly relates to an equal uncertainty in mass flow.

Another problem associated with temperature measurement and, hence, adding to mass flow uncertainty, is the difference in temperature between the measuring point and the flowmeter. For accurate conversion, the temperature at the flowmeter must be known.

Although viscosity is also temperature dependent, it is not as sensitive to temperature changes as specific gravity, for typical temperatures encountered in test cells. At extremes of temperature, particularly -30°F (-34°C) and below, viscosity changes more rapidly with temperature and becomes a critical parameter.

The final data acquired is the frequency output of the turbine flowmeter. The use of reluctance (rf type pickoffs) and the instrumentation that is associated with their use, provides an excellent signal for measurement. The signal is typically a 5 volt square wave, that can be measured with a frequency counter or frequency to DC converter. The accuracy of measured results is dependent on the technique chosen.

The method used at NAPC for steady state measurement is to count pulses of the signal as well as pulses from a stable clock signal for a predetermined period of time and ratio the two results for a very accurate frequency measurement. This frequency is acquired directly by the computer.

For transient (time varying) data acquisition the frequency from the flowmeter is converted to an analog voltage level proportional to the frequency using a frequency to DC converter. The analog voltage level is then acquired by the computer through an analog to digital converter. This method is less precise than the steady-state method.

For control room monitoring, the frequency output of the flowmeter can be displayed on a variable time base frequency counter. This is the least precise method of measurement in use at NAPC.

F. <u>DATA PROCESSING</u>

During the development of the NAPC fluid flow measurement technique, many areas have been addressed. The most significant is the data processing. Originally each flow calibration was treated separately. Since both the calibration and the measured parameter were based on weight, a separate calibration for each specific gravity to be encountered had to be kept. In the investigation of techniques to provide the capability of measuring fuel flows at elevated temperatures, fluid substitution was considered for the calibration. It was found, subsequently, that good correlation could be obtained if a function based on volume was used. This section of the report discusses the process of developing the current technique, the various data acquisition techniques available, and accuracies associated with them.

Initially, flowmeter calibration was done using the liquid that would be used in application and calibrating the meter using pounds as a correlation factor. This technique was required because of the limited range of the flowmeter and an inability to correlate more than one calibration at different temperatures to a single curve. For extreme temperatures the meters were calibrated at those temperatures, curves were developed, and in applicaton, hopefully, the meters were used at those temperatures. Figure 6 shows the effects of changing fluids and temperatures on weight calibrations. Problems and expense were incurred to run the extreme temperatures. Typically -30°F (-34°C) and -60°F (-50°C) were required. Running these temperatures required refrigeration and a great deal of time for stabilization. Lines in the calibration system frosted resulting in condensation and moisture problems in the flow bench.

The other extreme of temperature, above 100°F (38°C), is above the flash point of the fuels. The calibration system used was vented to the atmosphere and demanded caution in running. An additional problem was found with higher temperatures. Almost as fast as the calibration was run, the fluid was changing density. The light hydrocarbons were evaporated out. If specific gravity measurements were not made before and after the calibration, no correlation could be obtained on similar calibrations made several days apart.

The requirement to run calibrations at temperatures up to 200°F (93°C) led to investigations that showed the only way to run the calibration with the weigh-time system was to locally heat the fuel at the flowmeter and cool it before it got back to the calibration bench. The heating and cooling requirements were unrealistic for the highest flow rates. It was decided to look for other techniques for flow correlation.

Discussions with flowmeter manufacturers indicated that a single curve for a flowmeter could be obtained using volumetric parameters and the single curve would cover the extended range. The curve is called the universal curve and is normalized by including viscosity in the function. See the section on Response Characteristics for detailed discussion.

Calibration data, when not processed as pounds per hour, was processed as pulses (meter output) per gallon and correlated with frequency (Hertz or cycles per second). The universal curve is a plot of cycles per gallon against frequency divided by viscosity. An investigation into the technique indicated that indeed good correlation could be obtained. However, some caution is required.

Figure 4 displays the meter output function (cycles per gallon) plotted against frequency. Figure 5 displays the same data normalized by using frequency divided by viscosity as the X-axis. This is the universal curve.

In the section on Response Characteristics of a flowmeter it was stated that increasing viscosity decreases the rotor rotation rate because of increased drag forces. Fluid flow rate combines with this effect. At low flow rates there is less force available to turn the rotor, so, for a given fluid there is a low frequency limit. Flow rates below the limit produce a non-linear response that tails away from the universal curve. The data in these regions is repeatable and valid and can be used in application, if the application fluid duplicates the viscosity of the calibration fluid. The frequency of the low end cutoff is dependent on meter size, and is lower for larger flowmeters.

After confirming that the universal curve was a valid technique, application work was started. There had been little or no problem in curve-fitting data for a single fluid calibration. However, when more viscosities were added and the response became more non-linear the polynomial curve fits previously used were inadequate to describe the function. Several transformations of the data were attempted to find a function that was suitable. Historically the cycles per gallon function was used because it could be manually plotted to show error or data deviation with high resolution. Computer data anlysis does not have that limitation and therefore gallons per minute divided by viscosity as a function of frequency divided by viscosity proved to be the best transformation. Figures 7a and 7b show the results of this transformation. Figure 7b is shown with linear scales and 7a has logarithmic scales which more evenly spreads the data. The data typically will fit a first degree curve with less than 1% deviation, and a sixth degree polynominal is sufficient to fit the data to less than $\pm$.05% deviation.

A least squares polynomial fit is used to generate coefficients to characterize the data. Other curve-fitting methods and transformations will be investigated in the future.

The data acquisition system at NAPC is such that the polynomial is used at run time to calculate fuel flow from the frequency and temperature information from the flowmeter. The temperature is used to calculate fluid density and viscosity and to calculate and correct for the flowmeter expansion. The on-line processing capability provides maximum accuracy, whereas less sophisticated techniques are adequate but less precise. (See Appendix C for further discussion.)

To provide the best flow data it is necessary to know where the meter is operating on the universal curve. Therefore, if a counter is used to acquire frequency information, data on fluid flow may be predetermined for particular frequencies if the fluid remains at a known temperature throughout the run. Specific gravity and viscosity are then constant, a specific section of the curve can be predetermined and a time base constant set into the frequency counter. The accuracy of the on-line data is dependent on the temperature of the fluid and how close that temperature is to the predetermined value.

The critical parameter in fluid flow measurement is temperature. Differences in temperature of $\pm 3^{o}$F affect specific gravity by $\pm$.15% of point. Error in pounds per hour fuel flow is affected directly by this percentage. Viscosity is also affected by temperature; however, it is not as straightforward to predict the effect of temperature differences on the result. For standard fuels, JP-4 and JP-5, generally there is a large tolerance to changes in fuel temperature. A 20^{o}F (10^{o}C) change in temperature affects the viscosity approximately one centistoke or less at temperatures above 20^{o}F (-7^{o}C). A one centistoke change does not alter the section of the universal curve to be used by a significant amount. For some of the newer fuels, RJ-4 and JP-9, that have higher viscosities, a similar change in temperature can result in a 5 to 10 centistoke change that does change the area of operation. In addition to shifting the section of the curve used, the higher viscosities contribute to the non-linearity of the meter and it becomes important to locate the area of the curve to be used. The restraint of temperature imposed by specific gravity is the most critical.

Appendix B provides detailed information on the processing used at NAPC. From batch information on the fluid to be used in testing, coefficients are established that characterize specific gravity and viscosity. Given a temperature at run time the specific gravity equation is entered to get specific gravity at run temperature. The equation for specific gravity was developed empirically from the ASTM table (Reference (11)). The run temperature is also used in the Walther equation to find viscosity. The Walther equation is from ASTM (Reference (12)). The final correction is for change of size of the flowmeter for extreme temperatures. The contribution is very small for temperatures from 40°F (5°C) to 80°F (27°C), and is based solely on metal expansion (See Appendix B)

TABLE OF SYMBOLS

(1) μ - Absolute Viscosity pound/second-inch

(2) ν - Kinematic Viscosity inch^2/second

(3) ρ - Fluid Density in pound mass/inch

(4) D - Pipe Diameter in inches

(5) fo - Output Frequency in Hertz (Hz)

(6) Re - Reynold's number

(7) V - Fluid Velocity in inch/second

(8) cSts - Centistokes

ITEM	DESCRIPTION	QTY
1	CONNECTOR	1
2	PICKOFF	1
3	LOCKNUT	1
4	RETAINING RING, SUPPORT	2
5	BODY	1
6	SUPPORT(DOWNSTREAM)	1
7	CONE	2
8	RETAINING RING, BEARING	2
9	BEARING	2
10	ROTOR	1
11	SHAFT	1
12	SUPPORT(UPSTREAM)	1
13	SPACER	2

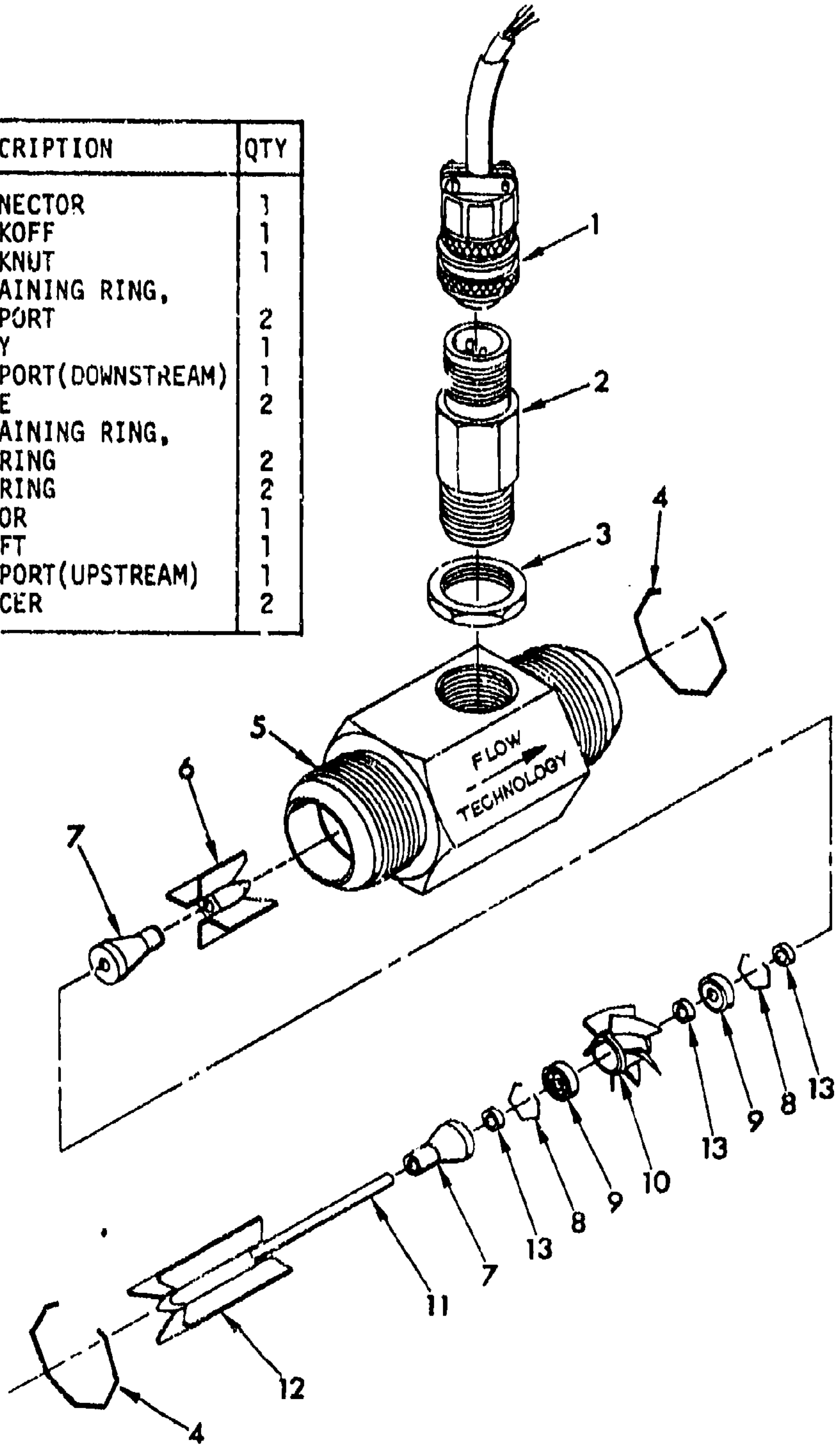


Figure 1. Complete Disassembly of the 3/4-inch through 2-inch Standard Line Turbine Flowmeter (Ball Bearing)

Courtesy Flow Technology, Inc., 4250 E. Brodway Road
Phoenix, AZ

Figure 2. Response Characteristics with Increasing Rotor Torque

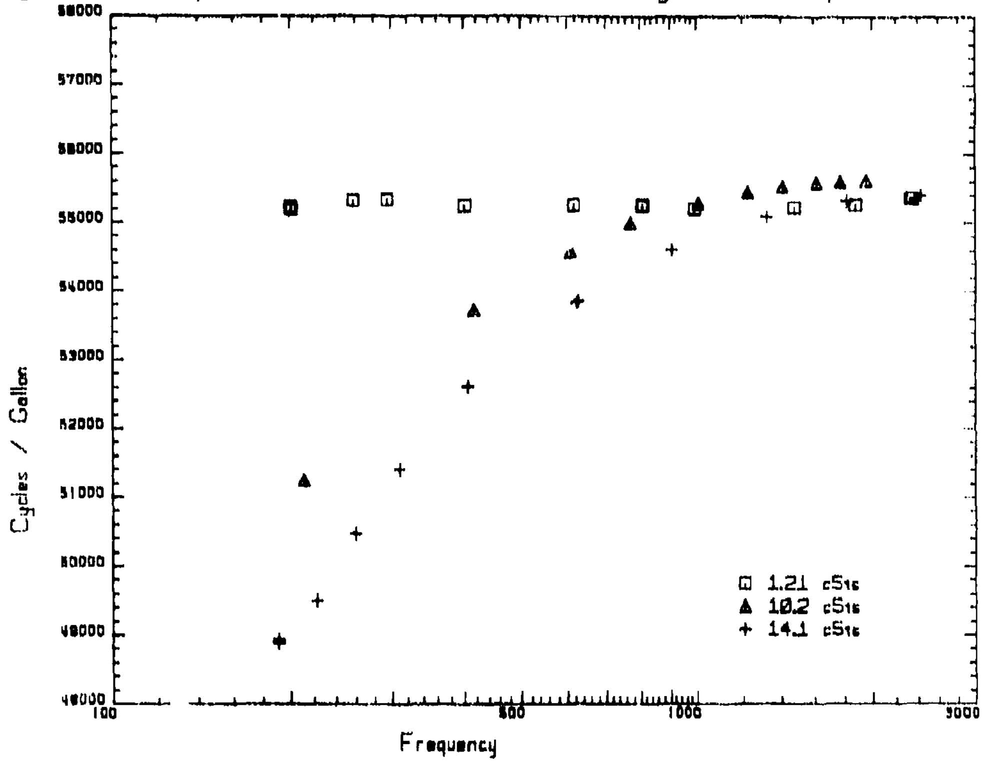


Figure 3. Response Characteristics Through Transition of Raynold's Number

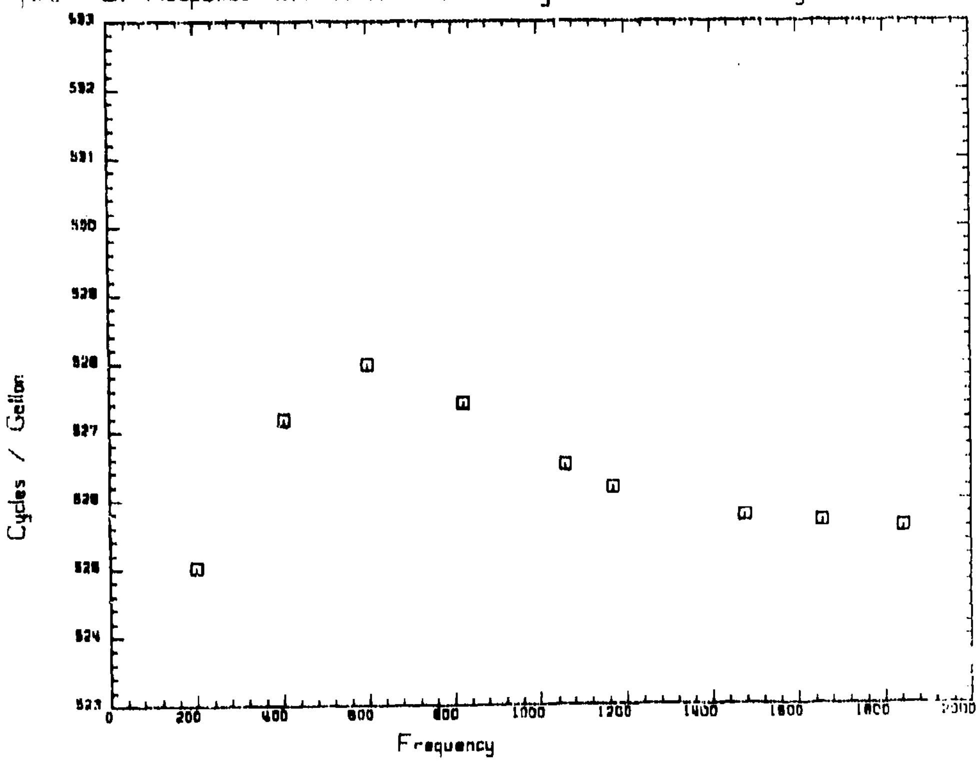


Figure 4. Response Characteristics for One Meter to Three Viscosities

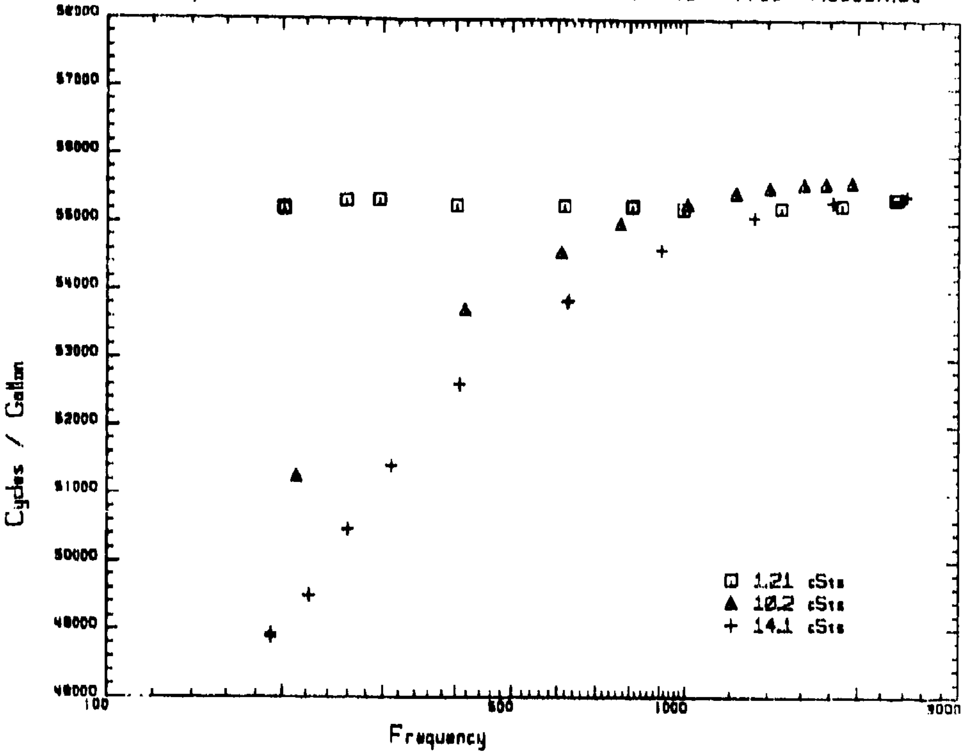
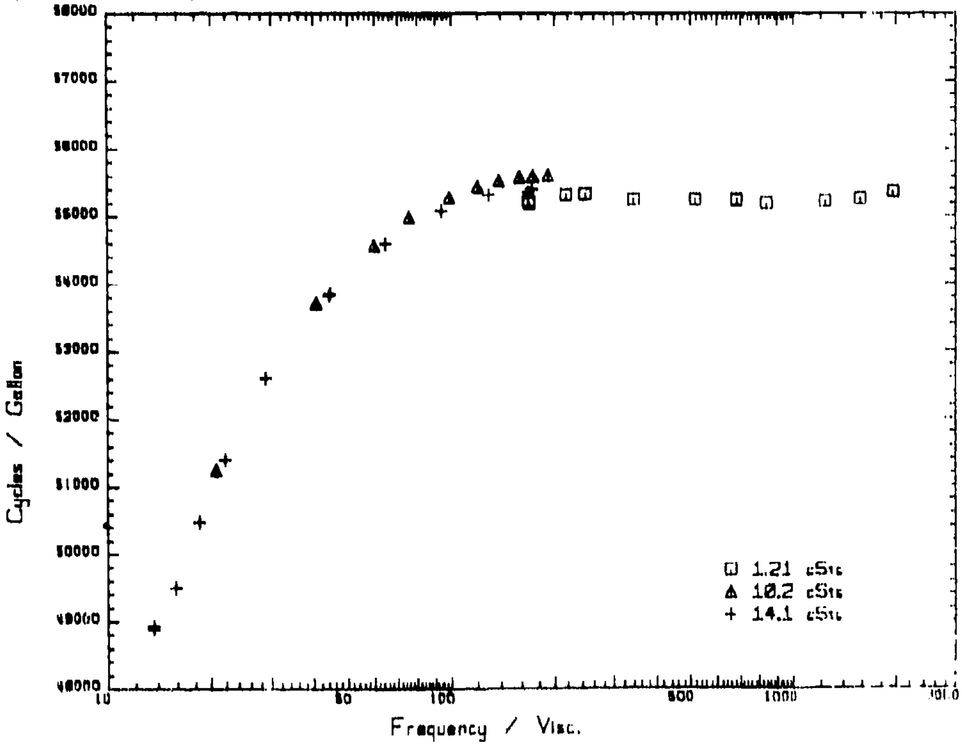


Figure 5. Response Characteristics when Normalized with Viscosity



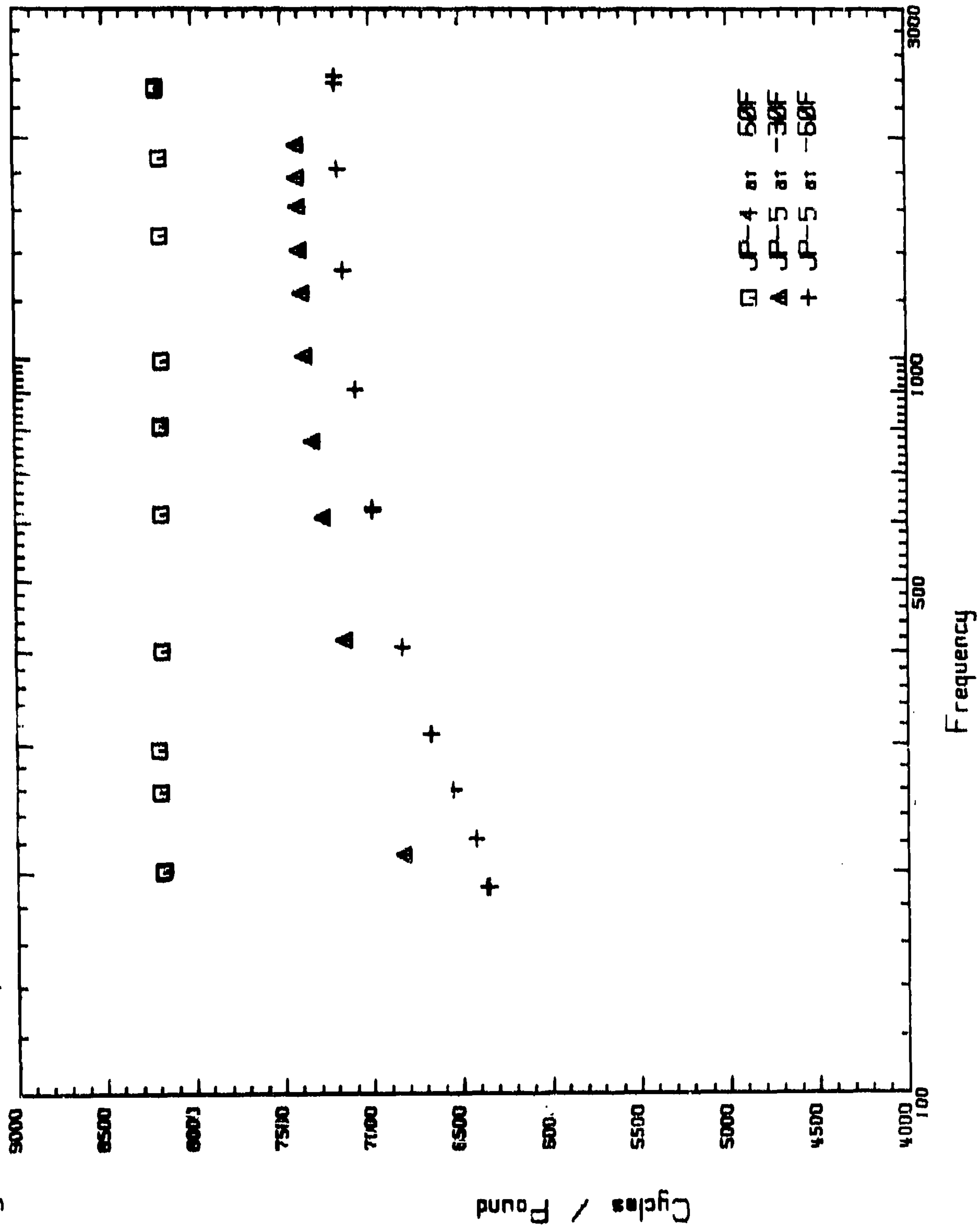


Figure 6. Response Characteristics with Data Shown in Mass Units

Figure 7a. Response Characteristics After Transformation to New Parameters

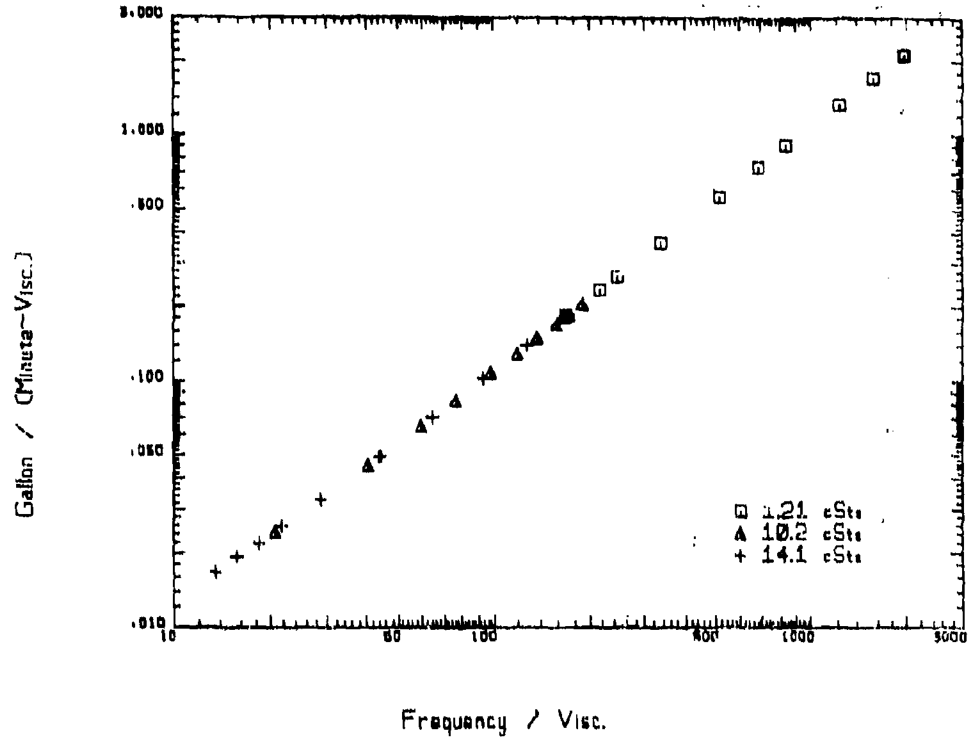
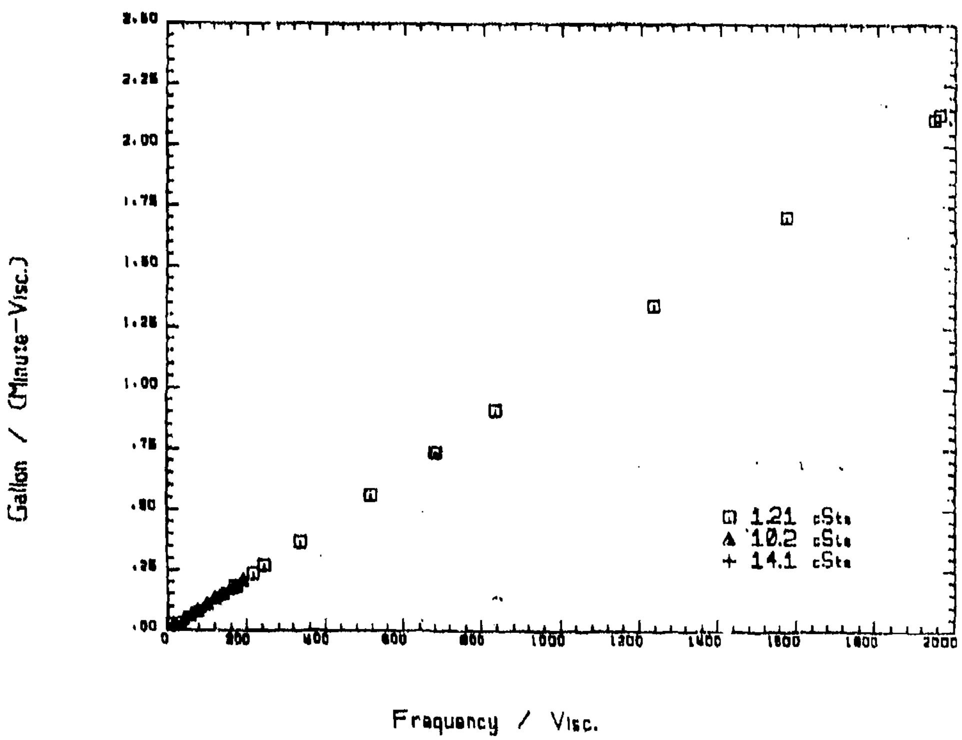


Figure 7b



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12. TABLES - "Viscosity - Temperature Charts for Liquid Petroleum Products", ANSI/ASTM D341-77

APPENDIX A

FLOW CALIBRATION FACILITY AT NAPC

The flow calibration facility at NAPC consists of a ballistic flow calibrator. The unit was manufactured by Flow Technology, Inc. and has been in use since May of 1978. The ballistic flow calibration technique consists of pushing a piston down a precisely bored cylinder. The piston pushes liquid through the turbine flowmeter with the flow rate controlled by throttling valves downstream of the flowmeter. A precise volume is determined by using pickoffs, similar to the turbine flowmeter pickoffs, placed on the cylinder to detect piston passage. Typically a pair of pickoffs, one to start and one to stop, is used to control the measurement cycle. The number of pulses from the flowmeter and from a stable clock are counted over the measurement cycle. Volume is preset into the machine. Data output on the console is frequency, gallons per minute flow rate, and cycles per gallon (calculated from the pulse rate, time and volume information acquired by the electronics).

Calibration data consists of the data from the console as well as temperature of the fluid. The temperature of the fluid is used to calculate the viscosity at run temperature.

To establish a complete curve for the flowmeter, a series of fluids are used that have viscosities from approximately one to 30 centistokes. The fluids used are Stoddard solvent (Mil 7024C) with a viscosity of 1 centistoke, hydraulic fluid (Mil 5606) with a viscosity of 20 centistoke and lubricating oil (Mil 23699) with a viscosity of 50 centistokes. Blends produce viscosities in between the pure fluids.

In order to provide on-line information on the viscosities, a viscometer has been added to the calibration facility. Calibration at two temperatures are run and the data included on the data sheet.

Future plans for the facility include a real-time data analysis and data acquisition capability. Currently the data is acquired manually for one flowmeter at a time although typically two flowmeters are installed. Data is keypunched to cards, and then batch processed on the computer. A data curve fit and analysis routine is then used to determine data validity. Typically it takes two to three days for a data validity check. With real-time capability any problem encountered could be corrected immediately.

A history of all calibrations for each flowmeter is retained so that as calibrations are added to the curve fit polynomials become more representative of the flowmeter performance.

Figure A-1 is a picture of a Ballistic Flowmeter Calibrator, courtesy of Flow Technology, Inc.

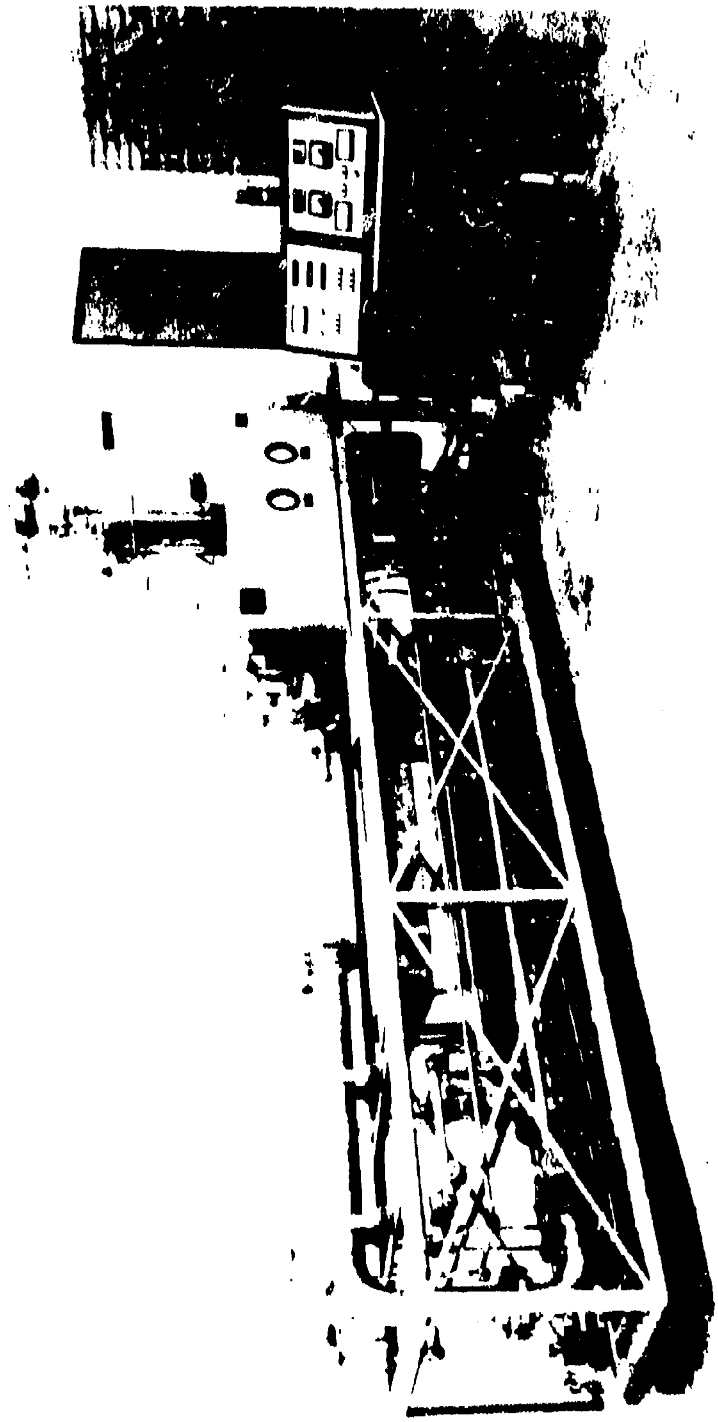

FIGURE A-1 BALLISTIC FLOWMETER CALIBRATOR (COURTESY FLOW TECHNOLOGY, INC.)

APPENDIX B

NAPC FUEL FLOW DATA PROCESSING

Figure B-1 is a calibration data sheet. Two sets of viscosity and temperature information, together with the temperature of the individual calibration points, are used to calculate viscosity at the calibration point. The other data is read from the ballistic calibrator console. It includes frequency (Hz), flow rate in gallons per minute (GPM), and a flow constant in cycles per gallon (CPG).

A. The processing used to reduce the calibration data is:

1. Convert measured temperature (^oF) to absolute (^oR)

$$T_1 = T_c + 459.69$$

2. a. Characteristic viscosity coefficients (A and B) for the fluid batch are calculated from the temperature-viscosity information [V(n) and T(n)]:

$$Z(n) = V(n) + .7 + C - D + E$$

where:

$$C = EXP(-1.14883 - 2.65868 \times V(n))$$
$$D = EXP(-0.00381308 - 12.564V(n))$$
$$E = EXP\ (5.46491 - 37.6289V(n))$$

and the expression:

$$\log \log Z(n) = A-B \log T(n)$$

is evaluated for the points to obtain the coefficients A and B. The process used is a least squares curve fit on a first degree equation.

b. The viscosity at the calibration temperature is then calculated by solving for Z in:

$$\log \log Z = A-B \log T$$

and evaluating:

$$\nu = Z1 - \exp(-.7487 - 3.295(Z1) + .6119(Z1)^2 - .3193(Z1)^3)$$

where $Z1 = (Z - .7)$ and ν = the viscosity

The calculations for viscosity are the Walther Equations from reference (1) and the Response Characteristics are from references (2) and (3).

3. The Calibration data is then converted to frequency divided by viscosity (Hz/ν) and gallons per minute divided by viscosity (GPM/ν). The log of this data, Hz/ν and GPM/ν, is curve fit using the least squares technique for a sixth degree equation. If the root mean square of the deviation and maximum deviation does not exceed .25% of full scale, the data is considered acceptable. As other viscosities are used in calibration, the data, if acceptable, is combined and coefficients are generated for the total data set.

B. When a flowmeter is to be used, viscosity and specific gravity information is acquired for the batch of fuel to be used. The viscosity data is processed to obtain characteristic viscosity coefficients in the same manner that was used for the calibration data. From the temperature at test time the same technique as was used for the calibration data is used to calculate test viscosity. Then:

$$Hz/\nu = Hz \div \text{viscosity}.$$

The polynomial, derived from the calibration data is evaluated to find GPM/ν. Then:

$$GPM = GPM/\nu \times \text{viscosity}$$

A correction factor is used to compensate for flowmeter expansion due to temperature.

$$GPM/_{Corr} = GPM\ (1 + .000025 \times (T_f - 70)$$

where T_f = Temperature of the fuel

Fuel flow in pounds per hour is calculated by:

$$PPH = 60 \times 8.3372 \times SGt \times GPM/_{Corr}$$

where 60 = conversion from minutes to hours

8.3372 = Pounds (mass) of water at $60^{o}F$ ($15.6^{o}C$) reference point for specific gravity

SGt = Specific gravity at fuel temperature

The specific gravity at temperature is found by the function:

```
X = SGB - .8        Y = TB - 25.

A1 = -.48812E-1-(.341198E-2*Y) + (.661208E-5*Y*Y)

A2 = -.76068E+1 +(.191023E-1*Y) + (.66639E-4*Y*Y)

A3 = .217558E+2 +(.258318*Y) - (.147465E-2*Y*Y)

B  = (A1 + (A2*X) + (A3*X*X)) + (4.24203) * .0001

SGT = SGB + B * (TB-T)
```

where

SGB = the Specific Gravity of the Batch at the temperature "TB" (supplied by MS33 engineer)

SGT = Specific Gravity of the fuel at temperature "T" for the measurement

REFERENCES

1. TABLES - "Viscosity - Temperature Charts for Liquid Petroleum Products", ANSI/ASTM D341-77.

2. HANDBOOK - "Kinematic Viscosity of Transparent and Opaque Liquids (and the Calculation of Dynamic Viscosity)", ANSI/ASTM D445-74.

3. TECHNICAL ARTICLE - "Viscosity", Measurements and Data, May/June 1975, p. C1-C13.

FIGURE B-1

Viscosity Data				Date			Meter I.D.	
Temp	Ctsks	Temp	Ctsks	Day	Mon	Yr	No.	S/N

Decimals & Commas Req'd

Close Valves

Temp	Hz	GPM	CPC

Size	No.	Vol.
3/8	06	
1/2	08	
5/8	10	.25
3/4	12	.5
1	16	1
1¼	20	2
1½	24	2
2	32	4

OPER

6/27/79

APPENDIX C

ACCURACY ESTIMATES

Using the processing discussed in Appendix B, NAPC predicts accuracies of:

PARAMETER	RANGE	RESOLUTION	PRECISION	BIAS	UNCERTAINTY
Fuel Flow:	(pph)	(pph)	(pph)	(pph)	(pph)
3/8-2.5	1000	<.5	.8	.57	2.17
3/8-5	2000	<1	1.5	1	4
1/2-10	4000	<2	2.5	2	7
5/8-15	6000	<3	3.5	3	10
3/4-25	10000	<5	5	5	15
1-50	20000	<10	10	10	30
1¼-75	30000	<15	15	15	45
1½-125	50000	<25	25	25	75
2-225	90000	<45	45	45	135

NOTE: The parameter name (ie. 3/8-2.5) consists of the flowmeter size (3/8) and its approximate maximum flow rate (2.5 gallons per minute).

In applications where less sophisticated data acquisition systems are used, less accuracy will be realized. The extent of the inaccuracy will be dependent on many variables.

The intent of the following paragraphs is to summarize data acquisition techniques and indicate areas of improvement or items that require particular attention to obtain the best accuracy.

The simplest data acquisition system consists of a counter for frequency measurement and some form of temperature measurement. Temperature is required to convert the gallons output of the meter to pounds. The flowmeter manufacturer provides a 'K' factor with the meter expressed in cycles per gallon. A frequency measurement divided by the 'K' factor provides a gallon per second number. It is important to note the viscosity of the fluid in this application. The 'K' factor is usually provided for a viscosity near 1 centistoke where the meter has its widest linear range. If fluids with viscosities greater than one are to be measured, the linear range of the flowmeter becomes smaller using the fuel. JP-5 at temperatures below 50°F (10°C) greatly reduces the linear range. Inaccuracies of over 10% are not uncommon with this type application.

A simple technique to improve the accuracy for these applications is to use the actual universal curve and estimate the area that will be used when running the higher viscosity fluids. The better the estimate the better the accuracy.

Specific gravity determination establishes the accuracy for the pounds per hour data. Specific gravity is very sensitive to temperature. In order to acquire pounds per hour to the highest accuracy, specific gravity at the fuel temperature is required. If a predetermined value is used, the closer the preselected temperature to the actual run temperature the higher the accuracy. A 3°F difference in temperature generates a 0.15% difference in pounds per hour measurement.

Fuel Batch information is used at NAPC for highest accuracy since it was found that fuels vary from batch to batch by significant amounts. In one experiment with JP-4 fuel, a 0.5% variation was noted in specific gravity after a portion of the batch was elevated in temperature. It is speculated that some of the lighter hydrocarbons boiled off, raising the density. It should also be noted that fluid specifications allow variations in specific gravity, viscosity, and other characteristic properties that can lead to errors if not taken into consideration.

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